OCEAN ACIDIFICATION

State of the Scotian Shelf Report

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The material in this document is co-published as:
MacLean M, Breeze H, Walmsley J and Corkum J (eds). 2013.
State of the Scotian Shelf Report. Can. Tech. Rep. Fish. Aquat. Sci. 3074.

First published October 2012

ISBN: 978-0-9881186-0-7

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1 ISSUE IN BRIEF

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This theme paper links to the following theme papers:

- >> Climate Change and its Effects on Ecosystems, Habitats and Biota
- >> Primary and Secondary Productivity
- >> Marine Habitats and Communities
- >> Trophic Structure

There is no more important geophysical relationship on Earth than that between our atmosphere and the ocean. The atmosphere overlies 100% of our planet, while the ocean covers 75% of its surface. This provides a large surface area in which the two interact. An interaction of particular importance is the movement of atmospheric gases into the ocean, which serves to balance their concentrations in the atmosphere. As such, an elevated carbon dioxide concentration in the atmosphere results in an elevated carbon dioxide concentration in the surface ocean (i.e., upper 100–200 metres or so) (Sabine et al. 2004; Royal Society 2005). As carbon dioxide dissolves in the surface ocean a certain proportion reacts with seawater to form carbonic acid, which is a weak acid that increases the dissolved hydrogen ion concentration and decreases pH. This phenomenon is commonly referred to as "ocean acidification" (Feely et al. 2004; IPCC 2007a). The relationship between the Earth's atmospheric carbon dioxide concentration and surface ocean pH is complicated by the ocean's ability to buffer carbonic acid formation (Caldeira et al. 1999). Buffering is a mechanism that can keep pH at a relatively stable level despite the addition of an acid, due to the presence of another chemical constituent that reacts with the acid to neutralize its presence. In the ocean, the principal buffering agent is carbonate. It acts to neutralize the presence of carbonic acid in the sea.

Over time periods greater than 10 000 years, marine ecosystems are able to regulate changes in ocean pH through carbonate buffering (Caldeira et al. 1999). Over shorter timescales the ocean can not easily respond. Today's concern regarding ocean acidification resides in its unprecedented rate of occurrence, due to the significant amount of carbon dioxide that has been added to the atmosphere over the past 250 years. Ocean acidification that occurs over a period of a couple of hundred years can show significant

[1] Ocean acidification is an effect of "ocean carbonation," which is the addition of atmospheric carbon dioxide to the ocean. Ocean carbonation, rather than ocean acidification, is perhaps a better characterization of the primary driver behind the range of marine-related impacts associated with increased atmospheric carbon dioxide levels.

negative impacts on the state of the marine ecosystem. Over the past 50 years, the atmospheric carbon dioxide concentration has increased by 75 parts per million (ppm) (NOAA 2011). This exceeds by100-fold a known period of similar rapid increase that occurred over a 6000-year time period following the last Ice Age (IPCC 2001; Royal Society 2005). Since 1750, ocean pH has decreased from 8.2 to 8.1, which is equiva-

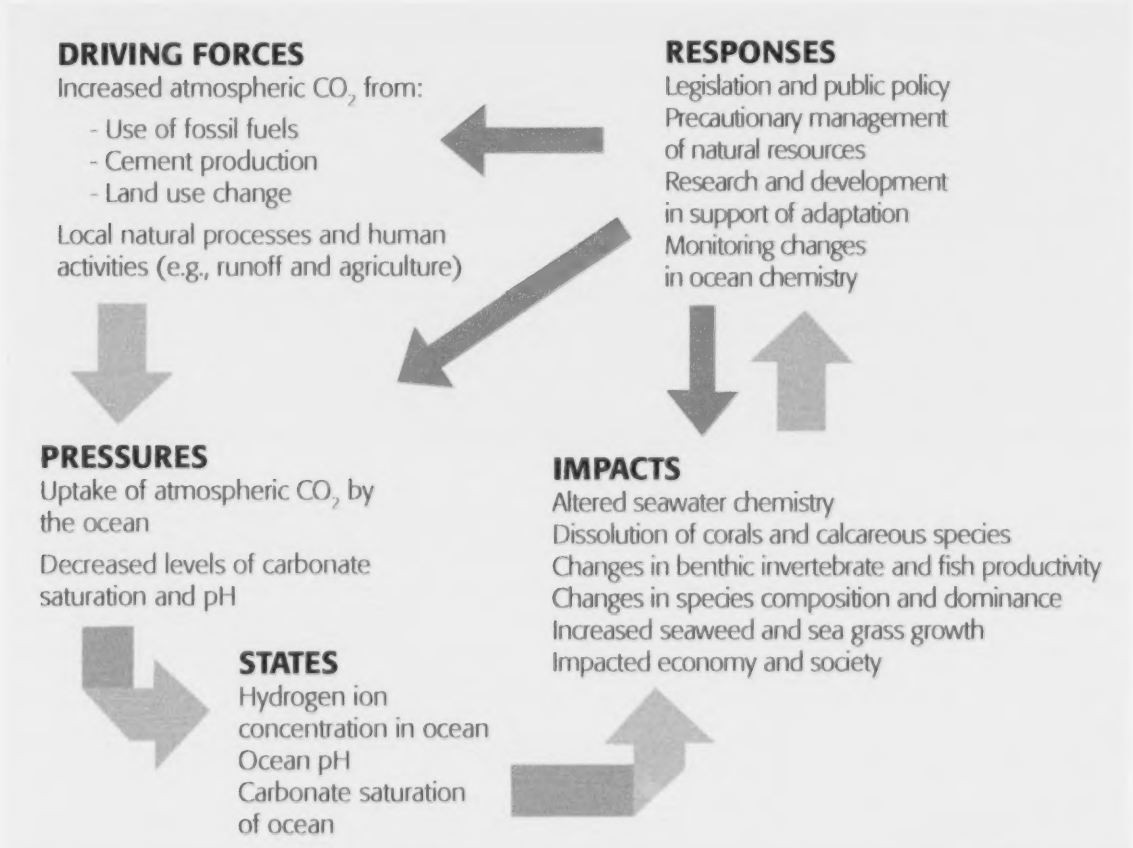

DRIVING FORCES
Increased atmospheric CO_2 from:
- Use of fossil fuels
- Cement production
- Land use change
Local natural processes and human activities (e.g., runoff and agriculture)
RESPONSES
Legislation and public policy
Precautionary management of natural resources
Research and development in support of adaptation
Monitoring changes in ocean chemistry
PRESSURES
Uptake of atmospheric CO_2 by the ocean
Decreased levels of carbonate saturation and pH
STATES
Hydrogen ion concentration in ocean
Ocean pH
Carbonate saturation of ocean
IMPACTS
Altered seawater chemistry
Dissolution of corals and calcareous species
Changes in benthic invertebrate and fish productivity
Changes in species composition and dominance
Increased seaweed and sea grass growth
Impacted economy and society

Figure 1. Driving forces, pressures, states, impacts, and responses (DPSIR) to ocean acidification on the Scotian Shelf. The DPSIR framework provides an overview of the relationships between the environment and human activity. According to the reporting framework, natural conditions and social and economic development (driving forces) exert pressures on the environment and, in doing so, the existing state of the environment is changed. Such changes can affect natural ecosystems, as well as humans that rely on ecosystems for their economic and social well-being. The changes, in turn, may elicit societal or government responses that influence other elements of the DPSIR framework.

lent to a 30% increase in the hydrogen ion concentration in the sea (Royal Society 2005). The potential effects of ocean acidification include altered seawater chemistry; decreased growth and productivity of calcium carbonate-based organisms; changes in respiration in large invertebrates, fish, and some zooplankton; increased growth of certain seaweeds and sea grass; changes in species composition and dominance; societal and economic impacts; and other potential impacts that presently remain unknown.

Science on the cause of ocean acidification is robust, while more studies regarding its potential effects on marine ecosystems are urgently needed (Royal Society 2005; Fabry et al. 2008; ICES 2008; CBD 2009; Doney et al. 2009; ICES 2011). A decrease in ocean pH is certain to occur over the coming century and longer due to present day atmospheric carbon dioxide levels, even with legislative or policy-driven reductions in carbon dioxide emissions to the atmosphere. Since a decrease in surface ocean pH and its associated impacts cannot be easily reversed, adaptive measures coupled with a reduction in carbon dioxide emissions to the atmosphere will have to be pursued to protect ecosystems and human livelihoods against this phenomenon. Examples of adaptive measures include the precautionary management of natural resources in the presence of uncertain ocean acidification-driven impacts, as well as research and development of methods and technologies that will allow vulnerable ocean industries and society to adapt to a changing marine ecosystem (**Figure 1**). The aim of this paper is to describe the cause and effect of global ocean acidification and what it may mean for the marine ecosystem of the Scotian Shelf region of Atlantic Canada.

2 DRIVING FORCES AND PRESSURES

To understand the present day concern over ocean acidification we must first understand some basic dynamics of carbon, the relationship between our atmosphere and ocean, and past patterns of ocean acidification. Carbon is found on our planet in the biosphere (e.g., plants and soils), atmosphere (e.g., carbon dioxide and methane), ocean (e.g., dissolved carbon, biota, and sediments), and underlying geology (e.g., petroleum and limestone). Through various natural and human-induced processes, carbon is continually moving in different forms between these pools. This is known as the carbon cycle (see Holmen 2000). In the atmosphere, carbon dioxide is fundamental to human survival by virtue of its role in retaining heat—it is a "Greenhouse Gas" (IPCC 2007b). Over the past two centuries, however, significant additions of carbon dioxide to the atmosphere have occurred due to fossil fuel combustion, cement production, and changing land-use patterns, all of which emit carbon dioxide to the atmosphere (Houghton and Hackler 2001; IPCC 2001; Royal Society 2005; CBD 2009).

Through these activities, humans are moving large quantities of carbon dioxide into the atmosphere, and, in doing so, significantly altering its natural distribution on Earth. Since 1950, the global population has almost tripled, increasing from 2.5 to 7 billion individuals in just over 60 years (UN DESA 2011). Over a similar time period, the atmospheric carbon dioxide concentration has increased from approximately 315 ppm to 390 ppm (**Figure 2**; NOAA 2011), with modelled estimates suggesting an atmospheric carbon dioxide concentration of approximately 700-1000 ppm by the end of the twenty-first century (the predicted range is attributed to different model scenarios). The emission of carbon dioxide, however, remains disproportionate amongst nations, with the industrialized and developing nations emitting more carbon dioxide per capita than the often more highly-populated underdeveloped nations. For example, Canada is home to only 0.5% of the global population yet it accounts for 1.5% of all carbon dioxide emitted to the atmosphere on an annual basis. Canada currently ranks ninth as a nation in annual total carbon dioxide emissions to the atmosphere (CDIAC 2012).

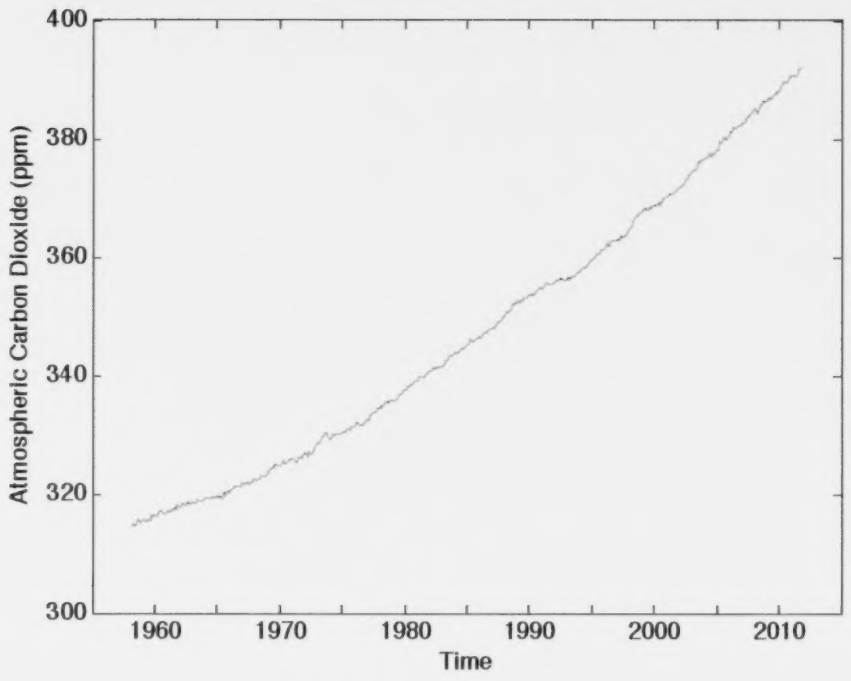


Figure 2. Atmospheric carbon dioxide concentration versus time since the late-1950s. Over the past 60 years, the atmospheric carbon dioxide concentration has increased by approximately 75 parts per million (ppm). The atmospheric carbon dioxide concentrations presented in this figure constitute measurements made at the Mauna Loa Observatory, Hawaii, by C. David Keeling of the Scripps Institution of Oceanography and the U.S. National Oceanic and Atmospheric Administration (source: NOAA 2011). This data has been reproduced with permission from the U.S. National Oceanic and Atmospheric Administration.

The timescale of carbon dioxide exchange from the atmosphere to the ocean is approximately a year (Wolf-Gladrow et al. 1999). This means an increase in the atmospheric carbon dioxide concentration readily translates into an increase in the dissolved carbon dioxide concentration found in the surface ocean. A product of increased carbon dioxide dissolution in the surface ocean is the formation of carbonic acid, which further dissociates in seawater to yield excess hydrogen ions that cause pH to decrease—"ocean acidification." The excess hydrogen ions then react with excess carbonate already found in the sea to form bicarbonate, which helps offset any change in pH—"carbonate buffering". In simple terms, pH is a measure of how acidic or basic a substance is. It is measured on a scale of 0 to 14, where a pH of 7 is considered "neutral" (e.g., purified water), a value less than 7 "acidic" (e.g., lemon juice), and a value greater than 7 "basic" (e.g., dish soap). At no time in the known past has the ocean ever been acidic (i.e., a pH less than 7), although it has fluctuated in its relative pH due to changes in the Earth's atmospheric carbon dioxide concentration (**Figure 3**, top panel; Caldeira et al. 1999; Pearson and Palmer 2000; Caldeira and Wickett 2003; Sabine et al. 2004). Aside from this global phenomenon, there are also regional and local drivers of ocean acidification, such as organic matter respiration, coastal runoff, and industrial activity, although these drivers are not discussed in this paper (see: Kelly et al. 2011; Mucci et al. 2011).

3 STATUS AND TRENDS

Globally, the atmospheric carbon dioxide concentration has varied from approximately 3500 ppm almost 60 million years ago to more constant values of approximately 100-400 ppm over the past 20 million years (**Figure 3**, top panel; Pearson and Palmer 2000). Over the 400 thousand years before the Industrial Revolution (circa 1750), the atmospheric carbon dioxide concentration ranged between 200-280 ppm (Feely et al. 2004). Since the Industrial Revolution, the atmospheric carbon dioxide concentration has increased by 100 ppm, reaching 380 ppm in 2000, with projected concentrations of 700-1000 ppm anticipated by the end of the twenty-first century (IPCC 2007b). In contrast, the average pH of the surface ocean has decreased from 8.2 to 8.1 over this same time period (Caldeira and Wickett 2005). By 2100, it is projected that pH will further decrease by an estimated 0.15-0.35 (**Figure 3**, bottom panel; IPCC 2007b). In total, between 1750 and 2100, pH of the surface ocean is predicted to decrease from 8.2 to 7.8 (IPCC 2007b).

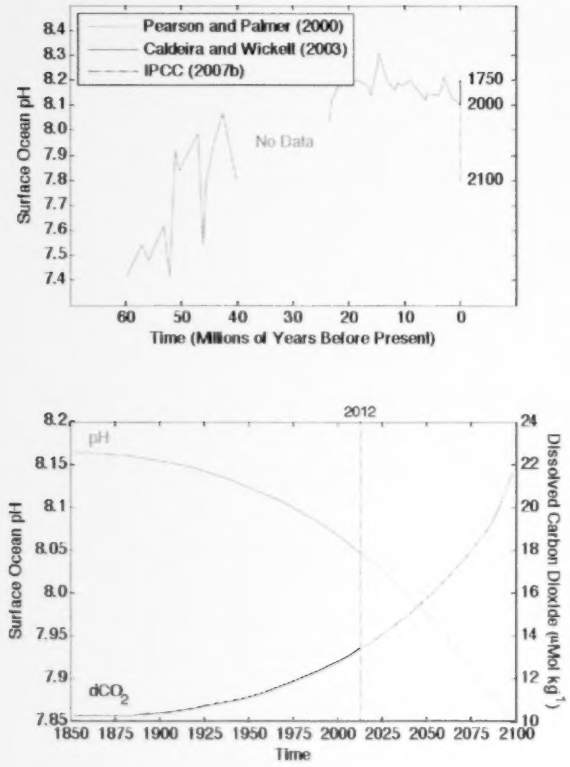


Figure 3. Surface ocean pH versus time. The upper panel demonstrates changes in surface ocean pH over the past 60 million years before present (solid red line), reproduced from data published by Pearson and Palmer (2000). The solid black line represents the change in pH since the Industrial Revolution (1750–2000 A.D.) (from Caldeira and Wickett 2005). The dashed black line is the predicted change in pH by the end of the twenty-first century forecast using a series of global climate models outlined by Meehl and others in the Intergovernmental Panel on Climate Change report published in 2007 (IPCC 2007b, see Figure 10.24 on page 795). On the upper panel, present time is considered to be 1750 A.D (i.e., present time equals zero on upper panel). The lower panel outlines observed (solid lines) and predicted (dashed lines) changes in ocean pH (red) and the dissolved carbon dioxide concentration in the surface ocean (black) from 1850–2100 (redrawn from Feely et al. 2006).

The ocean is a major sink for atmospheric carbon dioxide. From 1800 to 1994, almost half of all carbon dioxide emitted to the atmosphere from fossil fuel consumption has been absorbed by the ocean (Sabine et al. 2004). Thirty percent of this is found in the upper 200 m and 50% in the upper 400 m (Sabine et al. 2004). In contrast, only 7% is found at ocean depths greater than 1500 m (Sabine et al. 2004). The North Atlantic is a global "hotspot" for atmospheric carbon dioxide absorption, accounting for 23% of the ocean's total uptake between 1800 and 1994, even though this region only constitutes 15% of the global ocean's surface area (**Figure 4**; Sabine et al. 2004). Between 1983 and 2005, the rate of atmospheric carbon dioxide entering the North Atlantic Ocean near Bermuda increased, while pH in the region decreased by 0.037 over the same time period (Bates 2007). On the timescale of the coming decades to centuries, considered an instant in geological terms, the ocean will continue to absorb significant amounts of carbon dioxide from the atmosphere, since atmospheric concentrations are expected to double relative to their pre-industrial levels over this time period. The anticipated result is a continued increase in carbonic acid formation in the surface ocean coupled with a continued decrease in dissolved carbonate levels and, hence, an accelerated decrease in pH (Sabine et al. 2004). Unfortunately, very few long-term ocean pH time series exist (Nye 2010).

The North Atlantic, with its exceptional capacity to uptake atmospheric carbon dioxide, will likely see greater rates of ocean acidification relative to other ocean basins, especially as its ability to buffer future carbonic acid formation is continually reduced through time. Because the Scotian Shelf is found in the North Atlantic Basin, it may be particularly vulnerable to increased atmospheric carbon dioxide uptake and the accompanying changes in pH. Observations of ocean pH on the Scotian Shelf over the past several decades demonstrate a general decrease through time (**Figure 5**). The decrease in pH observed in Scotian Shelf waters is slightly greater than the average global ocean decrease observed over the same time period, although the cause of this remains unknown (DFO 2009). Many fac-

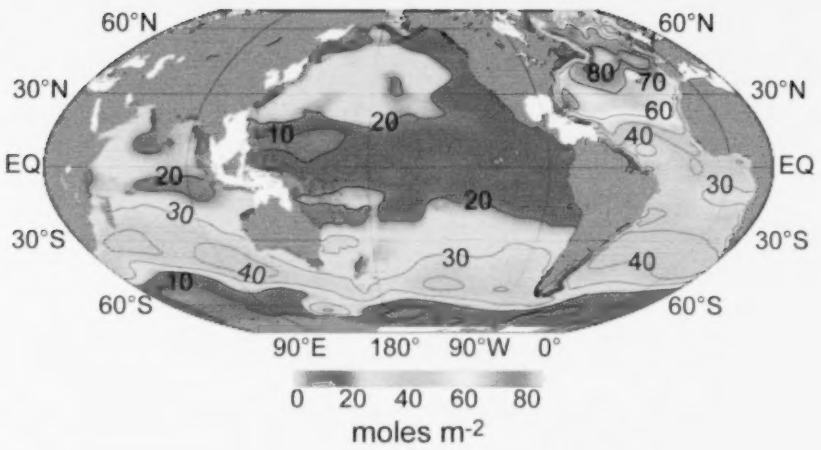


Figure 4. Atmospheric carbon dioxide concentration from anthropogenic sources entering ocean surface waters between 1800-1994 (Sabine et al. 2004). Waters of the North Atlantic are a major sink for atmospheric carbon dioxide, accounting for 23% of the total global ocean uptake over this time period despite constituting only 15% of the global ocean's surface area (Sabine et al. 2004, reprinted with permission from the American Association for the Advancement of Science).

tors influence global climate, making it difficult to predict how the marine environment will change. The unique oceanographic environment of the Scotian Shelf as a general convergence zone between several very different water masses makes it even more difficult to determine the rate and degree to which waters of the region may acidify. Although the effects that ocean acidification may have on the marine ecosystem of the Scotian Shelf are uncertain, a concern remains that any potential impacts could be severe (ICES 2011).

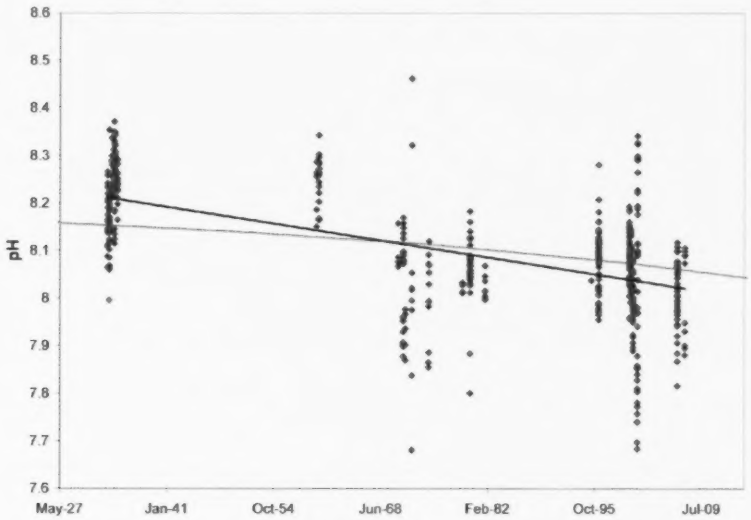


Figure 5. Decrease in pH on the Scotian Shelf over the past century. Time is reported in month and year (DFO 2009). Blue data points represent pH measurements from various locations on the Scotian Shelf, the black trend line indicates a decrease in pH with time, and the pink trend line represents the mean global ocean decrease in pH over the same time period.

4 IMPACTS

There are many potential impacts that could result from ocean acidification on the Scotian Shelf. At present, the body of scientific literature on potential effects remains limited in available field observations, while much of the existing observations are based on laboratory studies of short duration and differing research protocols (Royal Society 2005; Fabry et al. 2008; ICES 2008; CBD 2009; Doney et al. 2009; ICES 2011). This has made comparison of existing observations difficult. To resolve this challenge, the research community has come together to agree upon standard research protocols and to share and discuss its results, with many new studies on the effects of ocean acidification being published each month (see EPOCA 2012). Notwithstanding, it remains difficult to generalize existing research results regarding the impacts of ocean acidification on marine ecosystems at large as, for example, similar species often show different responses to ocean acidifica-

tion between regions. On the Scotian Shelf, this task is made even more difficult due to a lack of scientific research occurring in this region on ocean acidification. **Table 1** provides examples of potential impacts resulting from ocean acidification that could occur on the Scotian Shelf. These are taken from scientific studies carried out in other regions of the ocean, although focused on marine attributes found on the Scotian Shelf.

Table 1. Potential impacts of ocean acidification that could occur on the Scotian Shelf.

ELEMENT	IMPACTS
BIOPHYSICAL IMPACTS	
Carbonate saturation	Decrease in surface ocean carbonate saturation. This, in turn, affects calcium carbonate solubility. The aragonite form of calcium carbonate is more susceptible to dissolution than calcite in the short term, making aragonite-based organisms more vulnerable.
Nutrients and toxicity	Alteration of nutrient availability such as nitrogen, phosphate, and iron, leading to changes in the availability of nutrients to marine organisms that rely on them for growth and prosperity.
Marine organisms	Calcareous-based marine organisms are vulnerable to changes in dissolved carbon dioxide concentration and pH due to increased dissolution (e.g., cold-water corals).
Benthic invertebrates	Increased dissolved carbon dioxide in seawater may affect benthic invertebrate respiration, making calcareous-based organisms more susceptible to dissolution.
Marine fish	Increased dissolved carbon dioxide in seawater may lead to increased levels of carbon dioxide in the body tissue of fishes, in turn, impacting their respiration, circulation, and metabolism.
Seaweed and sea grass	Certain marine seaweeds and sea grass may exhibit increased growth rates due to increased dissolved carbon dioxide in the sea.
Ecosystem structure and function	The compounding effects of climate change (e.g., acidification, warming, and stratification) on multiple aspects of the marine ecosystem poses the greatest uncertainty, although it is believed ocean acidification alone will be enough of a driver to alter species composition and dominance in a manner that could profoundly alter marine ecosystem structure and functioning.
SOCIO-ECONOMIC IMPACTS	
Marine fisheries	Shellfish comprises the majority of the annual landed fishery value in Nova Scotia, with many of the shellfish species found on the Scotian Shelf potentially being vulnerable to ocean acidification due to their calcareous-based structures (e.g., American lobster and sea scallop).
Marine aquaculture	Many aquaculture species currently being harvested in Nova Scotia are potentially vulnerable to ocean acidification due to their calcareous-based structures (e.g., blue mussel, American oyster, and quahog clam).

4.1 SEAWATER CHEMISTRY

Much of the surface ocean is saturated in dissolved carbonate. Ocean waters decrease in dissolved carbonate concentrations with depth. At some depth, there is a boundary above which the dissolved carbonate is in excess (i.e., oversaturated) and below which carbonate is in deficit (i.e., undersaturated)—the boundary between "excess" and "deficit" is known as the "carbonate saturation horizon" (Royal Society 2005). The saturation horizon varies in depth throughout the global ocean due to differences in temperature and pressure, much as a snow line may vary in height on mountain tops due to differences in temperature. Today, dissolved carbonate concentrations in the global ocean are at the lowest levels believed to have existed over the past 800 000 years (IAP 2009). As discussed above, dissolved carbon dioxide in the sea reduces the carbonate concentration due to its buffering mechanism. It is predicted that productive surface waters of the Arctic Ocean and Southern Ocean will be undersaturated in essential carbonate minerals by 2032 and 2050, respectively (CBD 2009).

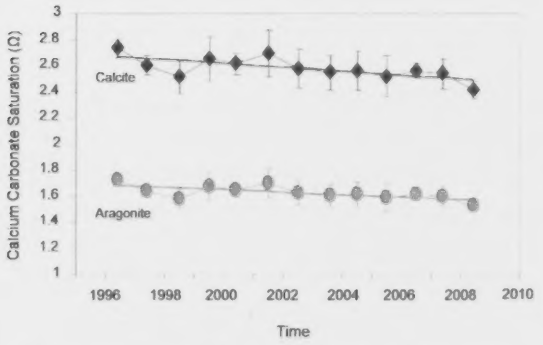


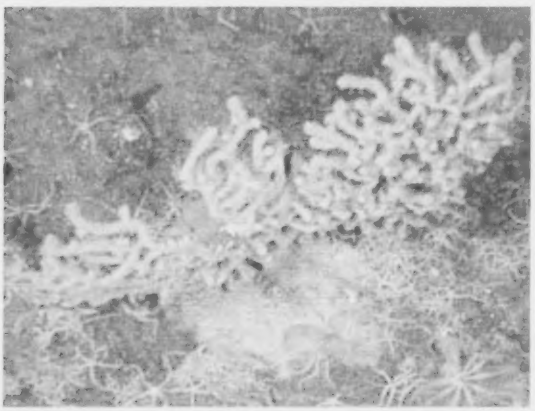
Figure 6. Decreasing calcite and aragonite calcium carbonate saturation state (Ω) of newly ventilated Labrador Sea Water through time. The boundary between oversaturation and undersaturation is denoted by a value of one on the figure (Ω=1), with calcite exhibiting a higher saturation state than aragonite.

Carbonate is an important ingredient in the formation of coral reefs, plankton shells, shellfish shells, and certain fish sensory organs by way of its reaction with calcium to form calcium carbonate. Calcium carbonate exists in the ocean in two general forms that are similar in chemical composition, but differ in their molecular packaging: calcite and aragonite. Of the two, aragonite is more soluble than calcite, so its saturation horizon is found much closer to the ocean's surface (Royal Society 2005). Long-term observations of the aragonite and calcite saturation states are not available for the Scotian Shelf, although observations from the nearby Labrador Sea demonstrate a general decrease in the aragonite and calcite saturation states over the past two decades (**Figure 6**). Similarly, waters of the lower St. Lawrence estuary have exhibited significant decreases in pH due to the increased accumulation of metabolic carbon dioxide in bottom waters (i.e., pH values near 7.7), decreasing both the calclite and aragonite saturation states in this region (Mucci et al. 2011).

Ocean acidification is also expected to alter seawater chemistry in a manner that affects the nutrients, trace metals, and toxins available to marine organisms (Royal Society 2005; Doney et al. 2009). Alterations in seawater chemistry may reduce the availability of phosphate, ammonia, and many other nutrients and trace metals that marine organisms rely on for growth (Royal Society 2005; ICES 2008). Similarly, it is believed an increase in the hydrogen ion concentration may increase the toxicity of select trace metals found in seawater. Predicting changes in seawater chemistry and its impact on marine species however is not straightforward. Changes in seawater chemistry of the Scotian Shelf may be more pronounced given its proximity to the carbon dioxide-enriched waters of the North Atlantic basin.

4.2 COLD-WATER CORALS

Cold-water corals rely on calcium carbonate formation to grow. Corals of the North Atlantic are particularly vulnerable to dissolution given the basin's status as a global "hotspot" for carbon dioxide uptake (see **Figure 4**). In the Atlantic Ocean, the aragonite saturation horizon



ranges from 0.5 to 2.5 kilometres below the sea surface, while the calcite saturation horizon ranges from 1.5 to 5 kilometres below the surface, depending on location (Royal Society 2005). Corals found at high latitudes and in cold waters are particularly at risk of dissolution, since they reside at depths and in water temperatures where carbonate saturation is already low and decreasing (Andersson et al. 2008). *Lophelia pertusa* coral is especially sensitive and vulnerable to dissolution (Royal Society 2005), with a study by Maier and co-authors (2009) demonstrating that at pH levels of 7.95 and 7.8, *Lophelia pertusa* demonstrated a reduction in its ability to form calcium carbonate by 30% and 56%, respectively. Results of the study also indicated the youngest and fastest calcifying corallites exhibited the greatest reductions in growth with decreasing pH. Models have suggested aragonite-based cold-water corals could reach their threshold of saturation in the coming decades (Andersson et al. 2008).

4.3 CALCIFYING MICRO-ORGANISM PRODUCTIVITY

Micro-organisms are small bacteria, phytoplankton, zooplankton, and invertebrate species. They are responsible for almost half of all global primary productivity (Rost et al. 2008). Primary productivity is the production of oxygen and other organic compounds. Micro-organisms are also the basis of the marine food web. Due to climate change, changes in dissolved carbon dioxide concentrations, pH, dissolved oxygen, temperature, and stratification will all combine to influence the composition and dominance of micro-organisms in the sea. This will impact their role in respiration, nutrient cycling, and many other important biological processes (Rost et al. 2008) (see Climate Change theme paper). In some instances, however, increased dissolved carbon dioxide in ocean waters could exhibit beneficial impacts on certain micro-organism species, due to varying respiratory responses. For others, more negative responses may be observed. In short, increased carbon dioxide dissolution in the sea is expected to affect micro-organism species differently, by impacting species-specific productivity, composition, assemblage, and succession (Orr et al. 2005; Rost et al. 2008).

Calcification is important to the prosperity of many micro-organisms by way of body structure, functioning, and protection (Pörtner 2008). Calcification is often a function of complex physiological processes in organisms that make use of bicarbonate or trapped carbon dioxide rather than carbonate, thus, although carbonate saturation may be a good proxy for calcification it is not necessarily a direct driver at the organism level (Atkinson and Cuet 2008; Pörtner 2008). Some calcareous-based micro-organisms can survive extended periods of time in the absence of their calcareous structures, while many oth-

ers cannot (e.g., echinoderms such as starfish) (Pörtner 2008). Typical calcareous marine micro-organisms include foraminifera (calcite shells), coccolithophores (calcite shells), and euthecosomatous pteropods (aragonite shells). They account for almost all of the flux of calcium carbonate from the ocean's surface waters to the deep sea (Fabry et al. 2008). Foraminifera and euthecosomatous pteropods are particularly important inhabitants of sub-polar regions such as the Scotian Shelf.

Micro-organisms vary in their response to ocean acidification, even within like species, and this has implications for the adaptation of individual species (Fabry et al. 2008). For lower trophic calcifying marine micro-organisms, such as *Emiliania huxleyi* (**Figure 7**), declines in their population may have significant implications on the ecosystem as a whole, by causing changes in food chain dynamics (Riebesell et al. 2000; Fabry et al. 2008; Rost et al. 2008). *Emiliania huxleyi* are commonly found in the waters of Atlantic Canada, including those on the eastern Scotian Shelf (Brown and Yoder 1994). The species is particularly vulnerable to changes in ocean pH. In general, acute and long-term sensitivity to dissolved carbon dioxide is likely to be highest in lower trophic invertebrate species, which are poorly-suited to tolerate changes that can influence important life processes such as calcification (Pörtner 2008). The result is a lower tolerance of these species to changes in temperature that will reduce their spatial distribution, associated species interactions, and affect their role in the ecosystem (Pörtner 2008). Pteropods are particularly vulnerable to ocean acidification due to their highly-soluble aragonite shells, while very little is known about the impacts of ocean acidification on cnidarians, sponges, bryozoans, annelids, brachiopods, and tunicates (Fabry et al. 2008). In contrast, increased dissolved carbon dioxide appears to have little impact on marine diatoms (Fabry et al. 2008). Some zooplankton species may exhibit diminished respiration, with species reliant on calcium carbonate showing signs of depressed physiological function (Royal Society 2005; Fabry et al. 2008; Rost et al. 2008).

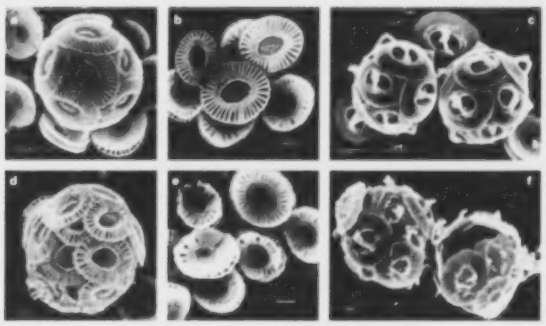
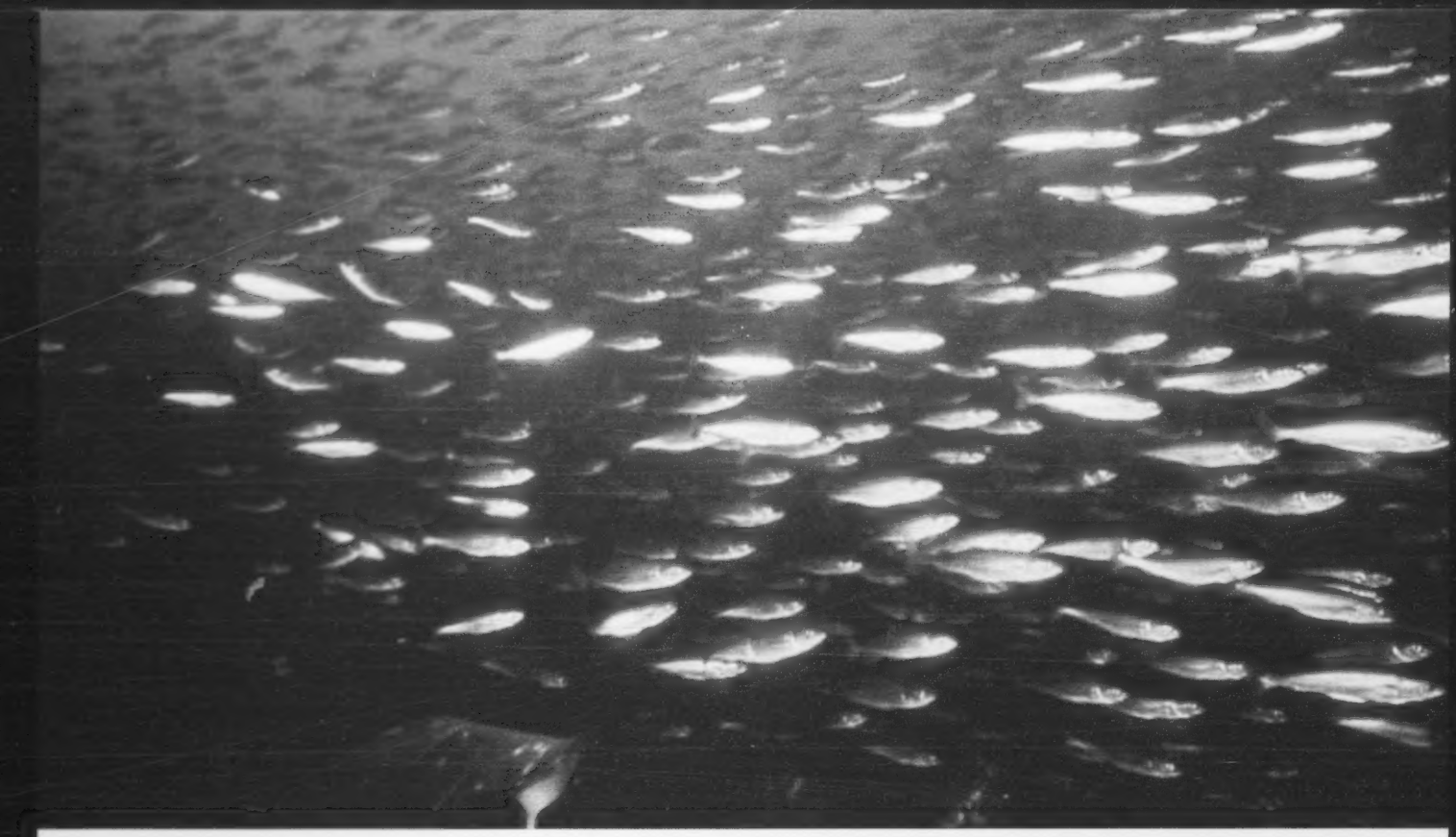


Figure 7. Evidence of reduced calcification in two calcareous marine coccolithophore plankton species: *Emiliania huxleyi* (see Panels a,b, d, and e) and *Gephyrocapsa oceanica* (see Panels c and f) (Riebesell et al. 2000). The organisms were exposed to simulated dissolved carbon dioxide concentrations of approximately 300 ppm by volume (Panels a–c) and 780-850 ppm by volume (Panels d–f), respectively. The scale bar represents 1 micrometre (µm) in length (one thousandth of a millimetre). At the higher simulated dissolved carbon dioxide concentrations, organisms demonstrated signs of malformation, as represented by abnormalities in their shape and roughness of their edges (reprinted with permission from the Nature Publishing Group, Macmillan Publishers Ltd: *Nature*, Riebesell et al. 2000).

Elevated dissolved carbon dioxide concentrations favour plankton species with high carbon demands and low surface area-to-volume ratios, that is, larger micro-organism species or species that lack carbon dependence. As a result, increased dissolved carbon dioxide may cause a shift in the global ocean's planktonic community structure (Wolf-Gladrow et al. 1999). For instance, non-photosynthetic micro-organisms such as bacteria, fungi, and protists may prosper under conditions of a lowered-pH sea. Many of these organisms have greater metabolic variability, which could give them a competitive advantage (e.g., nitrogen-fixing cyanobacteria may benefit from ocean acidification) (Royal Society 2005). This could further contribute to an altered chem-



istry of the sea (Orr et al. 2005). Last, increased dissolved carbon dioxide in the sea may increase the extra-cellular polysaccharides found on surfaces of plankton organisms. Extra-cellular polysaccharides behave as a glue that binds multiple organisms into large aggregates, subsequently altering the residence time and flux of planktonic biomass from surface waters into the deep sea (Royal Society 2005). As a result, essential minerals and energy found in the surface ocean could also dramatically change.

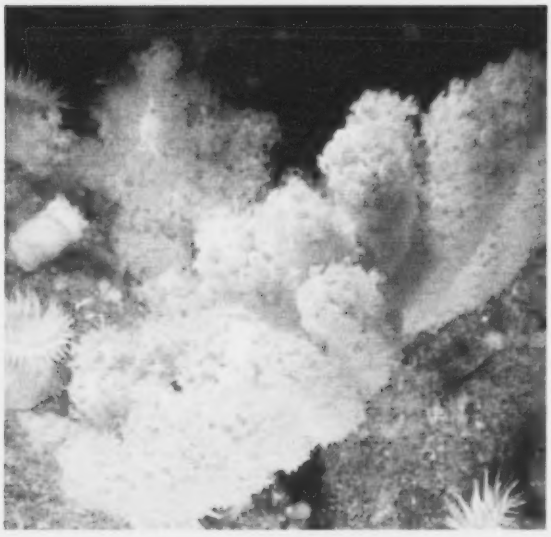
4.4 BENTHIC INVERTEBRATES AND FISH

Increased dissolved carbon dioxide in seawater may alter respiration in large invertebrates and marine fish, making it more difficult for them to remove carbon dioxide from body tissues and fluids, leading to internal acidification (Royal Society 2005). This in turn affects their ability to carry oxygen in the blood, which can lead to a decrease in cellular activity, respiratory activity, and rates of protein synthesis (Royal Society 2005). Both large invertebrates and bony fish (teleost) demonstrate similar responses to reduced ocean pH at the cellular level. However, individual fish are better suited than large invertebrates to fully compensate for cellular disturbances resulting from increased carbon dioxide in their blood and tissues (hypercapnia) (Pörtner 2008). Laboratory experiments demonstrate that early life stages of large, calcifying marine organisms, including echinoderms (e.g., starfish, brittle stars, sea urchins, and sea cucumbers), bivalves (e.g., scallops, mussels, clams, and oysters), crustaceans (e.g., lobsters, crabs, shrimp, and krill), and corals are vulnerable to ocean acidification during the fertilization, cleavage, larval settlement, and reproduction stages (Kurihara 2008). Tolerances related to climate-related impacts, however, are often very different between species and their life stages (e.g., larval versus adulthood) (Pörtner 2008; Ries et al. 2009).

Many calcifying benthic invertebrates that provide ecosystem and socio-economic benefits may be vulnerable to ocean acidification. Examples of such organisms include mussels, oysters, echinoderms, and select molluscs (Fabry et al. 2008). For instance, in laboratory experiments, Gazeau and co-authors (2007) demonstrated a 25% decrease in calcification rates in blue mussels (*Mytilus edulis*) exposed to dissolved carbon dioxide concentrations predicted to be observed by the end of the twenty-first century. Blue mussels are an important species to the aquaculture industry of Atlantic Canada (Innes et al. 2012). Aquaculture of blue mussels is found along the shores of Nova Scotia, with many of the province's coastal embayments on the south shore, eastern shore, and Cape Breton Island being suitable for blue mussel cultivation (NSFA 2012). Similarly, commercially-important scallops and oysters contain aragonite, so may be vulnerable to ocean acidification, as is true for calcite-based organisms such as sea urchin, lobster, crab, and shrimp (Cooley and Doney 2009). These invertebrates are found in waters of the Scotian Shelf.

Table 2. Reported response of select species vulnerable to changes in dissolved carbon dioxide concentrations and pH. Many of the species are important to the commercial fishery and aquaculture industries of Nova Scotia, although species-specific results often do not translate equally between different regions of the sea. To date, none of the following species found on the Scotian Shelf have been tested directly or have had Scotian Shelf-specific results published in the literature. See Tables 2 and 3 in CBD (2009) for other responses of a broader range of benthic and pelagic marine species to ocean acidification.

COMMON NAME *(SPECIES NAME)*	LIFE STAGE	EXPOSURE AND DURATION	pH	EFFECTS	REFERENCE
Lobster (*Homarus americanus*)	Adult	CO_2 = 409–2856 parts per million (ppm) for 60 days	Not Available	Increased net calcification rate with exposure to increased carbon dioxide concentration	Ries et al. (2009)
Sea scallop (*Placopecten magellanicus*)	Egg	Exposure not available. Exposed for 5 hours	less than 7.5	Polysperm (egg fertilized by more than one sperm) and slow cleavage rate	Desrosiers et al. (1996)
Blue mussel (*Mytilus edulis*)	Adult	CO_2 = 421–2351 ppm (by volume) for 2 hours	7.46–8.13	Decreased calcification rates of up to 25% with decreased pH	Gazeau et al. (2007)
	Adult	CO_2 = 409–2856 ppm for 60 days	Not Available	No change in net calcification rate with exposure to increased carbon dioxide concentration	Ries et al. (2009)
American oyster (*Crassostrea virginica*)	Larval	Exposed to varying hydrochloric acid concentrations for ten days	6–9.25	At pH less than 6.75 the growth rate decreased and at pH less 6.25 mortality rate increased	Calabrese and Davis (1966)
Quahog clam (*Mercenaria mercenaria*)	Larval	Exposed to varying hydrochloric acid concentrations for ten days	6–9.25	At pH less than 6.75 the growth rate decreased and at pH less 6.25 mortality rate increased	Calabrese and Davis (1966)
	Juvenile	CO_2 = 50,000 ppm (by volume) for 21 hours	7.1	Shell dissolution	Green et al. (2004)



Fish appear to have more resilience to accommodate changes in pH over the short-term compared to large invertebrates and micro-organisms, although more prolonged studies on fish critical life stages are required (Ishimatsu et al. 2008). In a recent study, Baumann and co-authors (2012) exposed early life stages of the estuarine fish *Menidia beryllina* to dissolved carbon dioxide concentrations anticipated in the latter half of the twenty-first century. The study demonstrated that the egg stages exhibited higher rates of mortality than the larval stage. Although studies of physiological processes in fish are limited, acidification can lead to reduced calcification, acidiosis, hypercapnia, and metabolic suppression (Fabry et al. 2008; ICES 2008; Doney et al. 2009). At present, regional studies are either underway or being proposed to investigate the effects of ocean acidification on lobster, crab larvae, and other fishes native to the Scotian Shelf. Preliminary results indicate that the local species of American lobster and Atlantic cod appear more vulnerable to ocean acidification than their European counterparts (E. Trippel, St. Andrews Biological Station, Fisheries and Oceans Canada, pers. comm.). **Table 2** outlines the response of select marine species that could be vulnerable to changes in dissolved carbon dioxide concentrations and seawater pH. Many of these species are important to the commercial fishery and aquaculture industries of Nova Scotia.

4.5 SEAWEED AND SEA GRASS GROWTH

Preliminary studies indicate that certain marine seaweeds and sea grass could exhibit increased growth rates due to increased dissolved carbon dioxide in the sea (Royal Society 2005). This is supported by the study of low pH, coastal hydrothermal vent environments, which exhibited high dissolved carbon dioxide concentrations and high sea grass production at a pH of 7.6 (Hall-Spencer 2008). Interestingly, shifts from coralline benthic communities to benthic communities dominated by sea grass and algae have also been observed in other marine areas of relatively low pH (Hall-Spencer 2008; Wootton et al. 2008; CBD 2009). These ecosystems are commonly characterized by low species diversity. Further research on this topic is required, since observations from such highly-specialized ecosystems generally may not be reflective of a lower pH ocean.

4.6 SPECIES COMPOSITION, DOMINANCE, AND ECOSYSTEM STRUCTURE AND FUNCTIONING

Ocean acidification-related effects may vary from impacts at the cellular level up to individuals, populations, and species, making it difficult to predict the compounding effects of climate change at the ecosystem level (Fabry et al. 2008; Pörtner 2008). Without question, ocean acidification will alter species abundance and composition leading to shifts in marine ecosystem structure and functioning over the long-term (Royal Society 2005). Species composition and dominance is determined by a combination of environmental factors such as predator-prey relationships, ocean currents, temperature, and nutrient availability and by species-specific factors such as passive versus active mobility. Ultimately, the nature of these intertwined relationships, and how ocean acidification and other natural and human-induced pressures may interact, will determine the resilience of an ecosystem to adapt to any change in the ocean's carbon dioxide concentration, pH, and carbonate saturation state (Guinotte and Fabry 2008; Pörtner 2008). The primary concern moving forward is how marine ecosystems will respond to ocean acidification, coupled with existing pressures associated with human activity (e.g., marine industries and pollution), natural variation (e.g., El Niño and La Niña), and other climate-induced impacts such as ocean warming (Pörtner 2008).

4.7 IMPACTS ON SOCIETY AND ECONOMY

The upper 1000 metres of the ocean contains most of the world's wild fish catch which, indirectly, supports fisheries aquaculture through the fish feeds it provides to this industry (Warren 2009). Preliminary studies suggest that climate change may result in a 60% turnover in global marine species biodiversity, with numerous local extinctions and simultaneous species invasions likely to affect a range of marine ecosystem services (Cheung et al. 2009). Ironically, humans' dependence on marine ecosystem services make them particularly vulnerable to the impacts of ocean acidification—fisheries and aquaculture being particularly noteworthy. In 2006, Nova Scotia fisheries directly employed 9500 skippers and crew, with shellfish accounting for approximately 80% of the total landed value of all captured fish species (Gardiner Pinfold 2009). The total landed value was $657 million, with approximately $525 million being attributed to shellfish landings such as scallop, lobster, and crab. Recall that shellfish may be particularly vulnerable to ocean acidification. Post-catch processing of commercial fishery landings in 2006 further employed 5700 full time equivalent positions (Gardiner Pinfold 2009). The total processed fish value was $900 million, with approximately $510 million in exports. Processing was primarily associated with shellfish landings (Gardiner Pinfold 2009).

In 2006, the marine aquaculture industry in Nova Scotia directly employed 440 full-time equivalent positions, with the primary species cultivated being blue mussels, American oyster, and salmon (Gardiner Pinfold 2009). Again, blue mussel and oyster may be particularly vulnerable to ocean acidification. The total harvested aquaculture value was

$42 million, with approximately $1.4 million in exports. Cumulatively, commercial fisheries, post-catch processing, and aquaculture contributed more than $1.1 billion to Nova Scotia's Gross Domestic Product in 2006, again with the majority of this being attributed to shellfish (Gardiner Pinfold 2009). Approximately $770 million supported regional household incomes (Gardiner Pinfold 2009). Not accounted for in the Gardiner Pinfold (2009) report was the number of indirect jobs associated with the fishing and aquaculture industries (e.g. seafood restaurants), which tends to increase dramatically from directed fishery catch and aquaculture harvesting up to post-catch processing, shipping, and retail (NYSG 2001; Cooley and Doney 2009).

In Nova Scotia, 3.4% of all employment in 2006 was directly tied to commercial fishing, post-catch processing, and aquaculture (Gardiner Pinfold 2009). Additional employment associated with the supporting transport and retail sectors also contributed significantly to the regional economy. Furthermore, there is value associated with the issuance of commercial fishery licences, fish processing licences, and aquaculture site leases (Cooley and Doney 2009). The number of issued licences in 2006 was approximately 3500, 290, and 350, respectively, totalling about 4100 issued licences associated with the fishing and aquaculture industries operating in the waters of Nova Scotia (Gardiner Pinfold 2009). Last, recreational fisheries and associated tourism also support regional economies through permitting fees, equipment, travel, lodging, and other associated sales and rentals (Cooley and Doney 2009). In Nova Scotia, rural economies are particularly dependent on fisheries and aquaculture for their well-being.

4.8 OTHER POTENTIAL IMPACTS

Many potential impacts of ocean acidification remain unknown due to a lack of research, such as a potential for change in the optical and acoustical properties of low pH ocean surface waters. For example, as tiny calcareous organisms that scatter light in the surface ocean become more susceptible to dissolution this may have significant effects on the transmission of light in the surface ocean (Balch and Utgoff 2009). It is believed that low frequency sound may also travel much farther, due to the absence of chemical constituents available to absorb low frequency acoustic waves. This could result in higher ambient noise levels found in the sea (Brewer and Heste 2009). What these effects may mean for marine species and ecosystems, however, largely remain unknown and in many instances are still under debate (Joseph and Chiu 2010; Udovydchenkov et al. 2010).

5 ACTIONS AND RESPONSES

Miles and Bradbury (2009) indicated that three challenges confront governments in responding to ocean acidification: 1) uncertainty in its effects; 2) decadal to centennial timescales in which effects may occur, with the effects only beginning to be observed towards the latter part of the twenty-first century; and 3) difficulty agreeing to a shared solution amongst nations, since the policies of any one nation cannot resolve ocean acidification alone. The response of global governments to address ocean acidification can be broken down into prevention and adaptation (Warren 2009). Prevention refers to a need to reduce carbon dioxide emissions to the atmosphere. Adaptation refers to a need to prepare humans and accommodate ecosystems for the effects of ocean acidification. In practice, both prevention and adaptation are required, since even a reduction in carbon dioxide emissions to the atmosphere today will not halt the effects of ocean acidification to come over the next few centuries.

5.1 LEGISLATION AND POLICY

Prevention of continued ocean acidification over the long-term is only possible through a reduction in carbon dioxide emissions to the atmosphere (Pacala and Socolow 2004). Changes in legislation and public policy that address land use change and our reliance on a carbon-based economy can promote emission reductions. In Nova Scotia, the *Environmental Goals and Sustainable Prosperity Act* (2007) mandates a 10% reduction in greenhouse gas emissions below 1990 levels and sets targets and timelines in which electricity sources are to come from renewable energy. If governments are to be prepared for the impacts of ocean acidification by the end of the twenty-first century, public policy choices need to be made now (Cooley and Doney 2009). The challenge

remains in the science community's ability to translate climate change research and development into meaningful policy options, balanced with economic considerations, which are readily understood by political decision makers and the public at large (Meyer 2012).

5.2 PRECAUTIONARY MANAGEMENT

Precautionary management targeted at the ecosystem level is advocated as a reasonable climate change adaptation solution (NOAA 2012). Marine protected areas (MPAs) are believed by many to be the most effective means to protect already vulnerable marine species and habitats from ocean acidification and other climate change impacts. A marine protected area is a coastal or marine area given special status to conserve and protect its natural habitat and marine life. Marine protected areas offer protection vis-à-vis limitations on human activities in their boundaries (Cooley and Doney 2009). This could allow ecosystems to accommodate changes in, for instance, ocean pH without facing additional human-induced pressures caused by activities such as fishing or offshore petroleum development. To date, MPAs and Coral Conservation Areas have been used to protect certain unique and vulnerable marine ecosystems on the Scotian Shelf (DFO 2012), although they have not been designed with the effects of ocean acidification in mind.

5.3 RESEARCH AND MONITORING

In support of greater research regarding climate change adaptation in Canada, the federal Treasury Board approved a funding package—*Helping Canadians Adapt to a Changing Climate*—in 2010 to complement previous federal government research initiatives on this topic. Fisheries and Oceans Canada (DFO) was awarded $16.5 million of funding over a five year period, with research to commence in 2011. The DFO research program is called the Aquatic Climate Change Adaptation Services Program (ACCASP). The ACCASP funding is being directed at three primary program components: 1) development of risk assessments to identify key marine vulnerabilities to climate change; 2) carry out ocean science research projects to increase understanding of future climate change and its impacts on ecosystems, infrastructure, and operations; and 3) development of systems and tools that support and promote climate change adaptation. At present (August 2012), research topics of interest are being identified, with some form of research regarding the potential effects of ocean acidification on commercial fish

and aquaculture species of the Scotian Shelf being anticipated. The research will expand upon long-term monitoring initiatives of the Scotian Shelf. It is anticipated this research program will help identify potential impacts of ocean acidification on the marine waters of the Scotian Shelf (and beyond) over the coming centuries.

INDICATOR SUMMARY

INDICATOR	DPSIR	POLICY ISSUE	ASSESSMENT[1]	TREND[2]
Use of fossil fuels	Driving Force	Increased use of fossil fuels leads to increased emissions of carbon dioxide to the atmosphere.	Poor	-
Carbon dioxide absorption by surface ocean	Pressure	North Atlantic ocean is a global "hotspot" for the absorption of carbon dioxide into the surface ocean.	Fair	-
Surface ocean pH of Scotian Shelf	State	Surface water of the Scotian Shelf is decreasing in pH at a rate greater rate than the average global ocean.	Fair	-
Calcium carbonate saturation	State	Saturation of calcium carbonate in waters that influence the Scotian Shelf (e.g., Labrador Current) is decreasing.	Fair	-
Invertebrate calcification rates	Impact	As pH decreases so does the ability of many invertebrates to maintain calcification rates necessary for survival at various life stages.	Unknown	?
Legislated targets for carbon dioxide emission reductions	Response	Legislated targets for carbon dioxide emission reductions would resolve ocean acidification over the long-term.	Poor	/
Research studies into ocean acidification (in Canadian context)	Response	The majority of research studies on ocean acidification have been completed since 2004, with many governments currently implementing research programs on this topic.	Fair	+

[1]Assessment: assessment of the current situation in terms of implications for the state of the environment. Categories are poor, fair, good, unknown.

[2]Trend: is it positive or negative in terms of implications for the state of the environment? It is not the direction of the indicator, although it could coincide with the direction of the indicator.

Data Confidence:
The science regarding the cause of ocean acidification is robust, while more studies regarding its potential effects on marine ecosystems are urgently needed. Some effects have been extrapolated from laboratory studies.

Key:
Negative trend: -
Unclear or neutral trend: /
Positive trend: +
No assessment due to lack of data: ?

Data Gaps:
Canada is only beginning to consider and evaluate the impacts of ocean acidification on marine species, ecosystems, and associated industries.

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